Diversity textile antenna systems for firefighters

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***Abstract*—Off-body communication systems are valuable to improve the security of rescue workers by allowing them to transmit vital information collected by sensors. As rescue workers often work in indoor environments characterized by many obstructions, non line-of-sight propagation with multipath effects and shadowing compromises the performance of the wireless communication. The reliability is enhanced drastically by the use of diversity techniques. In the measurement campaign presented, the performance of such an off-body diversity system is compared for two antenna configurations: two dual-polarized antennas, versus four circularly polarized antennas. The actual data transmission confirms the marginal difference between the two configurations, suggesting the use of dual-polarized systems for reasons of user convenience and ease of practical implementation.**

***Index Terms*—body-centric, diversity, textile antennas, ISM**

I. Introduction

Wearable textile systems are developed to enhance safety and security of rescue workers. These systems collect data concerning the wearer's life signs and his nearby environment, which are then wirelessly communicated to a base station or to another rescue worker. This off-body communication is valuable for firefighters operating in a building. However, an indoor environment gives rise to a fading channel where multipath and shadowing effects cause the signal levels to fluctuate severely as the firefighter is moving around while working.

The communication link ought to be reliable as vital information is involved. The quality of the link can be significantly improved by using diversity techniques to combine signals transmitted and/or received by multiple antennas. The use of dual-polarized antennas offers the practical advantage of handling two signals on a simple compact antenna patch. However, the diversity gain resulting from polarization diversity can be different in comparison to the diversity gain resulting from spatial diversity by using two antennas physically separated by some distance. Nevertheless, an important advantage of the dual-polarized system is that the number of antenna patches needed is reduced to half the diversity order, which is very convenient in a practical application.

Measurements and/or analyses for off-body diversity systems were discussed in literature before in [1]–[8] and specifically for polarization diversity in [9], [10]. However, a different type of antennas was used and no actual data transmission was documented. Often the measurement time involved per sample is too long, hence the measurements inadvertently include the effect of time diversity, resulting in an overestimation of the performance. In our opinion it is of paramount importance to verify the performance of a proposed diversity scheme by means of a real data transmission, including all imperfections of a real transmitter and a real receiver, such as e.g imperfect synchronization, carrier and channel estimations. In our practical experiment a wireless link, transmitting quadrature phase-shift keyed (QPSK) data at 2 Mbits/s is realized.

Fig. 1. Front (1), back (2) and upper arm (3,4) patch antennas integrated in the fire-fighter's garment. Antennas (1,2) are oriented perpendicular to antennas (3,4).

In the following measurements the performance of two dual-polarized antennas [11] is compared to the performance of four spatially separated circularly polarized patch antennas [12] on a firefighter's body. Two measurement series are performed under similar conditions, where a firefighter's outer jacket is equipped with the following flexible foam-based antennas:

1) Four circularly polarized antennas, one at the front, one at the back and one on each upper arm as illustrated in Fig. 1.
2) Two dual-polarized antennas, one at the front and one at the back, as in Fig. 1, but now only antenna locations 1 and 2 are used.

Both antenna types are designed to operate in the 2.45 GHz ISM band, which corresponds to a wavelength of about 12 cm, leading to antenna patches of a convenient size.

The antenna patch and the ground plane are manufactured out of e-textiles so that the system can be integrated into the firefighter's jacket in a non-obstructive way.

The fireman receives signals that are transmitted by a fixed base station equipped with a vertically polarized dipole antenna. The transmit configuration is identical for both measurement sessions.

The performance of the wireless link significantly improves by using diversity techniques that combine the four signals received by the patch antennas (using, e.g., maximal ratio combining). In a real-life measurement, data are transmitted and received for which we determine the signal strength and the number of bit errors. The performance is then compared for the two on-body antenna configurations.

The measurement sessions lead to the interesting conclusion that the minor decrease in performance when using the dual-polarized configuration is small enough to justify the use of this more compact system for reasons of practical convenience and ease of implementation.

II. Measurement results

Measurements are performed along a path with non line-of-sight (NLoS) propagation. This path is situated at a distance of approximately 17 m from the transmitter ($P_{tr} = 100mW$) and oriented perpendicularly to the direction of the transmitter. The path is obstructed by brick walls and office equipment, both causing fading and shadowing. Earlier measurements by our team [13], [14] confirmed the multipath propagation present in this area and indicated a nearly Rayleigh distributed fading pattern. In these measurement campaigns, measurements were also performed along line-of-sight (LoS) paths. However, in comparison to a LoS situation, the NLoS path proved to be much more demanding for the receiving system.

The instantaneous channel response for each transmitted burst is estimated based on pilot symbols. Bit error rate graphs are calculated for the different antenna configurations and compared to each other, as well as to the theoretical graphs for a Rayleigh fading environment. The theoretical graphs are calculated for independently and identically distributed signals. In a practical situation the performance is suboptimal, mainly due to correlation of the channel gains but also because of small differences in the statistical distribution of the gain for different channels.

For off-body communication, unequal gain is partially caused by the antenna configuration. For a walking person, antennas mounted at a different height on the body consistently experience different shadowing by the environment.

A. Statistical distribution of the signal levels

Both measurements with the two different antenna configurations were performed consequently and in the same environment. Fig. 2 displays the cumulative distribution function (CDF) for both measurement sets and also the theoretical CDF for a Rayleigh distributed signal. The three curves are very similar. Differences below the 1% level are related to the limited number of recorded signals, as is apparent from the steps visible in this area of the plot.

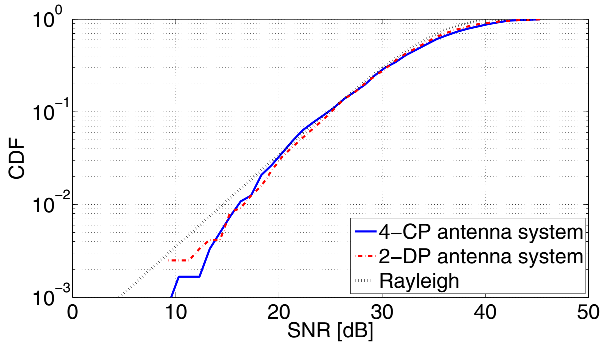

Fig. 2. Cumulative distribution function for the input SNR for the four circularly polarized antenna system (4-CP antenna system) and the dual dual-polarized antenna system (2-DP antenna system) measurement campaigns, compared to the theoretical CDF for a Rayleigh distribution.

B. Signal-to-noise ratios and bit error rates

Fig. 3 and 4 display the signal-to-noise ratios (SNRs) and bit error rates (BERs) for each received data burst for both diversity antenna system configurations. The SNRs fluctuate partially independently during the course of the measurement. The BER values for the input signals are shown in the bar graphs below. The bottom bar graphs display the BER after maximal ratio combining (MRC), note that the scale is different here.

For these graphs Gaussian noise was added to the received samples to artificially lower the average SNR to 12 dB per input port, causing a sufficiently large number of bit errors to visualize the real-time performance of the diversity systems for each individual data burst. Without the addition of noise the BER for the input signals is too good to demonstrate the real-time diversity gain. The addition of noise produces SNRs similar to those that would be received when transmitting at a lower power. The advantage of this approach is that all plots are based on the same set of data.

The graphs display the real-time performance increase obtained by using diversity, as the bit error performance is shown for each received burst. The bit error rate resulting from the two configurations with MRC is equal, this MRC BER corresponds to 7 errors in the 237600 transmitted bits.

Note that the noise has been added to the signal before processing. This means the BER values shown in the graph result from a complete receiving process including timing, frequency and phase estimation errors on the noisy signals. Because of these effects, the MRC BER is not as low as predicted by the theory. The impact of channel estimation errors increases with noisier signals and reduces the performance of MRC. However, the performance of MRC is still very good in this practical situation as more than 98% of the transmitted bursts are received error free for both configurations at an average SNR of 12 dB per receiver input port, corresponding to a transmitted power of 0.1 mW.

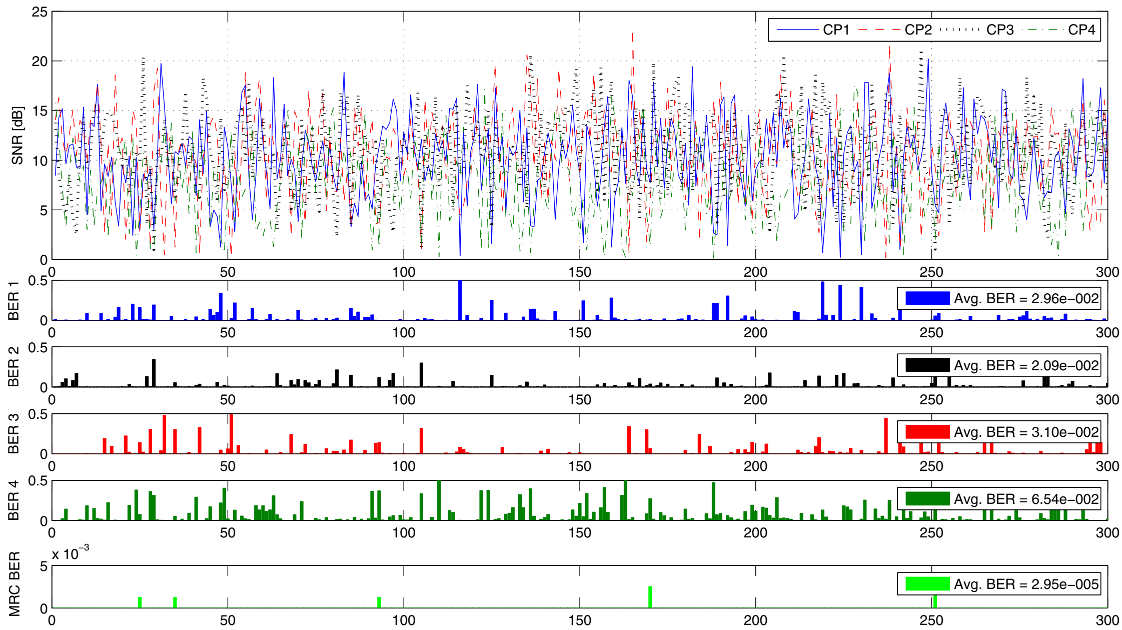

Fig. 3. SNRs and BERs for the reception with four circularly polarized patch antennas.

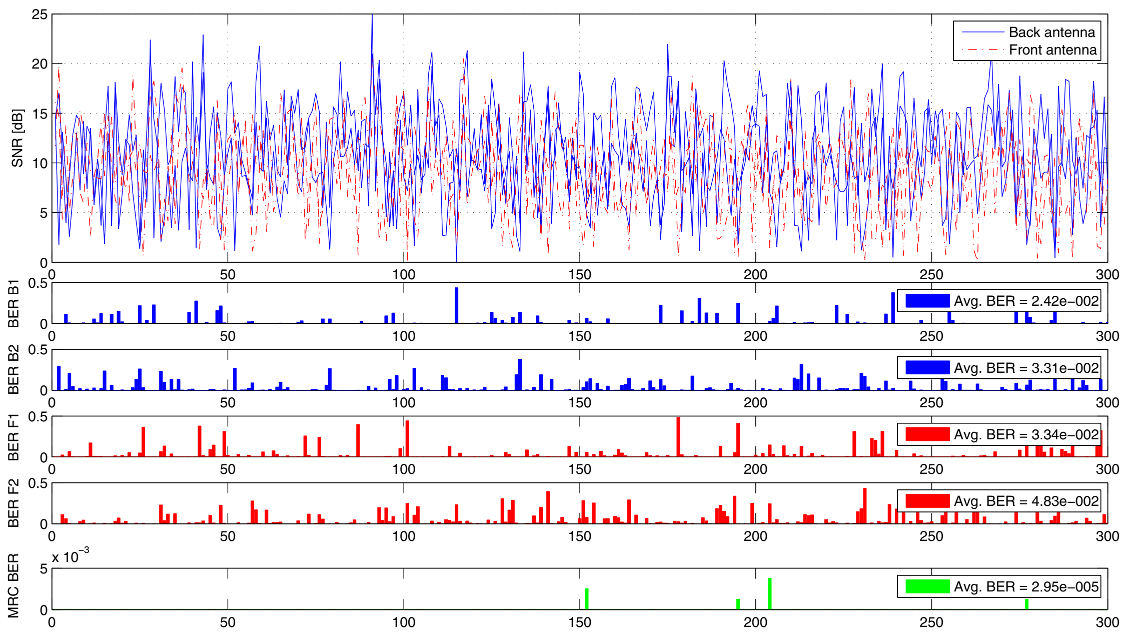

Fig. 4. SNRs and BERs for the reception with two dual-polarized patch antennas.

C. Signal envelope correlation

The signals that are received by the different antennas inevitably have a degree of correlation. The signal envelope correlations calculated for the measurements are listed in Tables I-II.

TABLE I
SIGNAL ENVELOPE CORRELATION FOR 4 CIRCULARLY POLARIZED ANTENNAS)

	1.Front	**2.Back**	**3.Left**	**4.Right**
1.Front	1.0000	0.0121	0.1869	−0.1185
2.Back	0.0121	1.0000	0.0381	−0.0507
3.Left	0.1869	0.0381	1.0000	−0.0561
4.Right	−0.1185	−0.0507	−0.0561	1.0000

TABLE II
SIGNAL ENVELOPE CORRELATION FOR 2 DUAL-POLARIZED ANTENNAS)

	1.1.Front	**1.2.Front**	**2.1.Back**	**2.2.Back**
1.1.Front	1.0000	0.4036	0.1771	0.0453
1.2.Front	0.4036	1.0000	0.2589	0.1413
2.1.Back	0.1771	0.2589	1.0000	0.3453
2.2.Back	0.0453	0.1413	0.3453	1.0000

A higher signal correlation means the signals are less complementary and results in a performance decrease for the diversity system. However, a correlation coefficient lower than 0.7 is often considered as an indication that a significant diversity gain is possible by combining the signals. All values are significantly lower than stated by this rule of thumb. Nevertheless, the highest correlation coeffients result from signals produced by both feeds of the same dual-polarized antenna. This explains why the dual-polarized system is slightly less performant. A degree of coupling is present between both signals of the same antenna. This coupling varies when the antenna is bent due to movements of the body.

Small differences in correlation for the other signal combinations should not be directly linked to a difference in performance, as the overall correlation is not the only factor having influence. The performance increase is obtained by array gain as well as diversity gain and both factors depend on the correlation in a different way.

III. BIT ERROR CHARACTERISTICS

Based on the distribution of the recorded signal levels, bit error characteristics are calculated for the different diversity situations. Detailed information about those calculations was presented in [13], [14]. The characteristics in Fig. 5 allow a comparison of the average performance of the antenna configurations. The curves from top to bottom correspond to an increase in performance (a lower BER for the same average E_b/N_0), the items in the legend are in the same order. The characteristics are displayed as a function of the average signal at the input ports and show array gain as well as diversity gain. These graphs indicate the performance to be expected for the measured distribution of signal levels, including correlation and unequal average channel gain. However, as the BER is calculated based on the SNR (unlike the real demodulation and detection in section II-B), perfect channel estimation is now assumed.

A. Fourth-order diversity

The three lower curves in the graph correspond to fourth-order diversity.

- The performance of the configuration with four patch antennas approximates the theoretical characteristic for Rayleigh fading channels with fourth-order diversity.
- The BER curve for the dual-polarized system is shifted to the right by only 1 dB, although only two antenna patches are used instead of four. The slightly compromised performance results from the higher correlation between the signals from both feeds of each dual-polarized antenna.

B. Second-order diversity

The set of curves situated in the middle represents the results for second-order diversity.

- The characteristic for 2nd-order diversity using the front and back circularly polarized antennas fits the theoretical curve for Rayleigh fading with second-order diversity.
- The curve for 2nd-order diversity using the left and right upper arm antennas indicates a slightly worse performance, in comparison with the previous system.
- The characteristic for polarization diversity is calculated based on the concatenation of the measurements for the front and back patch antennas. However, when combining the signals only polarization diversity for signals originating from the same patch is used. The curve corresponds to the average behavior for one dual-polarized antenna providing two signals to be combined. An additional decrease in performance is visible, compared to the previous configuration.

The above comparison is intended to highlight the differences between the configurations. Despite these minor differences, it is clear that all three configurations perform well in realizing 2nd-order diversity

C. No diversity

The upper curve is a reference curve, corresponding to the average signal on the input ports. This curve approximates the theoretical curve for Rayleigh fading. This also corresponds to the results for the CDF in Fig. 2.

IV. CONCLUSIONS

The measurements clearly demonstrate the excellent performance of a fourth-order diversity receiving system at 2.45 GHz using two dual-polarized textile patch antennas on the front and back of the body. The characteristic for the system using four separate antennas is only shifted to the left by 1 dB compared to the dual-polarized system, where the latter one conveniently only needs two antenna patches. The bit error rate characteristics for both fourth-order diversity systems approach the theoretical characteristic for Rayleigh fading with fourth-order diversity, including array gain. The practical data transmission test confirmed the marginal difference in real-time performance for both configurations.

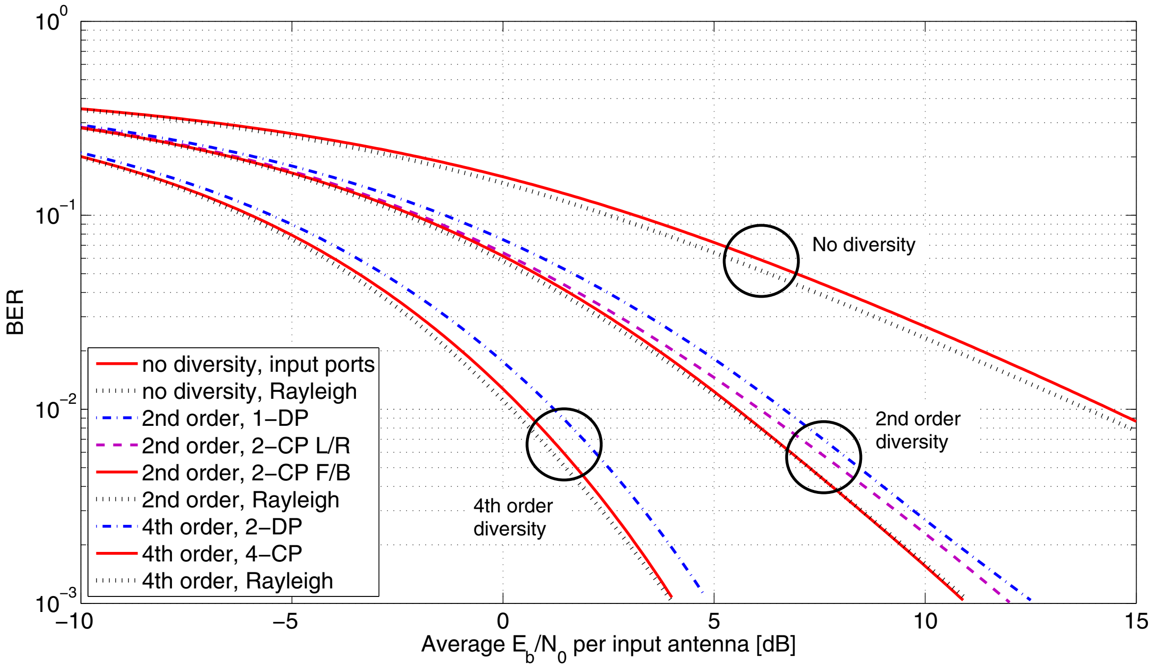

Fig. 5. BER characteristics, from left to right as ordered in the legend; for the different antenna configurations and for the theoretical characteristics for Rayleigh fading.

For a second-order diversity system, similar conclusions are drawn, second-order diversity can clearly be achieved while using only one dual-polarized antenna patch. Using different patches offers some increase in performance, depending on the position of the antennas used.

The measurement illustrates that the front and back torso are the best positions when using only two patches. The left and right arm antennas perform slightly worse in comparison. For the front and back antennas the body provides extra isolation, for the left and right arm antennas the body's shadowing effect is smaller.

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